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INTRODUCTION TO BASIC SOLAR CELL MEASUREMENTS

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ABSTRACT

The basic approaches to solar cell performance and diagnostic measurements are described. The light sources, equipment for I-V curve measurement and the test conditions and procedures for performance measurement are detailed. Solar cell diagnostic tools discussed include analysis of I-V curves, series resistance and reverse saturation current determination, spectral response/quantum yield measurement and diffusion length/lifetime determination.

INTRODUCTION

The accurate, reproducible evaluation of solar cell performance is one of the more difficult and challenging aspects of device development. The short circuit current of a solar cell is strongly dependent on the intensity and spectral distribution of the illuminating source. The problem arises because all available light sources (the sun included) change intensity and spectrum with time. Control of this variable system is possible although filled with many subtleties. Once the experimental challenges of obtaining an accurate device short circuit current have been overcome, the current-voltage (I-V) characteristic and hence the power output and efficiency can be obtained. However, this next step is also subject to errors. Key to eliminating these errors is the understanding that the solar cell is a power producing device. Thus electrical connection to the solar cell is an important consideration. Finally, the assessment of device performance and understanding of the mechanisms which limit cell performance is the final step that leads to improved device performance.

It is the purpose of this paper to present a general overview of solar cell performance measurement and diagnostic techniques. It is wise for all solar cell investigators to review such basics periodically to guard against the infusion of poor, expeditious techniques that inevitably result in confusion.

CHARACTERIZATION OF SOLAR CELL PERFORMANCE

First, and by far the most critical parameter to be determined in accurate solar cell performance measurement, is the short circuit current. This parameter is controlled almost exclusively by the light source used and the way its level is adjusted. Considerations on the light sources available and the way to adjust them will be covered subsequently. The next important consideration is the electrical aspects of the circuitry and connections made to the solar cell. Their discussion also follows. The intertwining of these areas is necessary before accurate, reproducible measurements of device performance can be made.

LIGHT SOURCES

The types of light sources generally used for solar cell measurement are listed in Table I. Natural sunlight is the most desirable; however, it is also the most complex and its availability cannot be assured. If, however, it is used, details of the appropriate measurement procedures to be used are described in reference 1. These measurements require the use of a reference cell or pyranometer to determine the irradiance. Critical atmospheric components such as water vapor and turbidity must be measured as well. They influence the spectral distribution of sunlight and hence affect the performance of the cell. A variation of about 5% in current can be caused by atmospheric variations. This variation occurs only when a pyranometer is used to monitor the intensity. The black body response of the pyranometer is sensitive to variations in spectrum outside the bandpass of the solar cell. It appears possible to reduce this error through mathematical modelling; however, such approaches have not been thoroughly investigated at this time. More reliable, accurate answers are obtained through use of a reference cell as intensity monitor. As long as spectral response of this cell is the same as the device under test, changes in atmospheric composition will not affect the results.

A second area of difficulty in natural sunlight measurements is translation of the cell performance curve to the recommended (1) standard reference conditions of 100 mW/cm^2 and 28^o C. This translation requires the intensity and temperature of the solar cell or module under test. The intensity is easily obtained from the reference cell. In general, measurements will not be made at 100 mW/cm^2; hence correction is necessary. Device temperature can be conveniently controlled for a single cell, but module or array temperature cannot, thus necessitating corrections. Curtis

(2) has discussed the problems and gives a realistic approach for obtaining accurate translated I-V curves from natural sunlight measurements.

Due to the variability of natural sunlight, artificial light sources are more convenient to use. The types of artificial light sources generally used in solar cell measurement are listed in table II. Tungsten sources are the least expensive, pulsed xenon lamps the most. Carbon arc lamps are not included here as they are unstable and contain too much ultraviolet light for good terrestrial simulation. All these light sources are capable of highly accurate, reproducible results. However, their spectral distributions do not exactly match terrestrial sunlight. Hence, all require a reference solar cell to set their intensity so as to minimize errors in short circuit current. A typical tungsten lamp/water filter solar simulator is shown in figure 1, The water filter is used to eliminate the sizable infrared component of the 3400^{0} K tungsten lamp. The ELH lamp simulator looks much the same, except for the elimination of the water filter. The water can be eliminated because the reflector around the bulb is coated with a dichroic filter that allows most of the infrared radiation to escape.

The test plane of a steady-state xenon arc lamp is shown in figure 2. These light sources can uniformly illuminate areas up to 30x30 cm. The pulsed xenon arc lamps can uniformly illuminate areas up to 5½ M diameter. All these light sources can achieve uniformities of $\pm$ 2% across the test plane. The spectral distributions have a reasonable match to terrestrial sunlight so that the consequences of not exactly matching spectral response of test and reference cell are not severe ($<$ 1%(3)).

Finally, with appropriate electronic controls, their intensity stability is good. The spectral distribution of several of these light sources, referenced to outer space sunlight is shown in figure 3. Curtis (3) has shown that the spectral distributions of these light sources have an adequate match to terrestrial sunlight. The spectral distribution of typical direct beam terrestrial sunlight is shown in figure 4. Failure to adequately match spectral distributions can lead to unexpected results as shown in figure 5. In this extreme example, use of a red wavelength light source completely distorts the performance characteristic of the device. Such an extreme mismatch in spectral distributions is unlikely; however, errors of several percent in magnitude are easily possible with an improperly matched light source especially when the test and reference cell spectral responses are not matched (3).

In summary, the major source of error in solar cell performance measurement is in short circuit current. Accurate measurement of this current requires care and control of a number of variables. When such control takes place, accuracies in current better than ± 1-2% are possible.

CURRENT-VOLTAGE CURVE MEASUREMENT

The general types of equipment that can be used to obtain a current voltage (I-V) curve are listed in table II. These are listed in order of increasing cost. Fixed load resistors allow only discrete points along the I-V curve to be obtained. The variable power supply (e.g., ref. 4) allows a continuous power curve to be obtained. Furthermore, this approach permits biasing of the cell in the forward and reverse direction to obtain additional diagnostic information. The electronic load is basically an automatic power supply tailored for solar cell use. The calculator-controlled system also uses a power supply to obtain the data. This system has the distinct advantage of speed in data reduction. In reality, this system produces answers, not just data.

This instrumentation, when properly maintained in calibration, is capable of faithfully and accurately reproducing device I-V characteristics. However, their output is only as accurate as the input they receive. The electrical connections to the device can distort the shape of the I-V characteristics obtained. This area represents the second most likely source of error. Any wire resistance developed between the test device and the instrumentation will cause losses in power output; hence, an inaccurate I-V curve. These losses can be almost entirely eliminated through use of four-wire connections to the cell (2 voltage, 2 current). With this approach, resistive losses in the wiring and contacts are eliminated because only the voltage at the terminals of the device is measured. However, in using these connections, care must be taken not to separate the voltage and current leads by a great distance or erroneously large fill factors will be obtained. It is also helpful if the current contacts can be as large as possible. This approach will, for the most part, eliminate resistive losses in cell circuitry.

SOLAR CELL DIAGNOSTICS

Once reliable I-V curves have been obtained, the investigator usually experiences several surprises. Most of these surprises occur because the shape of the I-V curve is not the clasic square shape as shown by the solid line in figure 6a. The solid curve is the data in the power quadrant while the dashed lines represent the reverse bias (left) and far forward bias (bottom) data. As unusual as they may appear, I-V curves are the first line of solar cell diagnosis. Other diagnostic data that can be obtained include series resistance, dark diode characteristic, reverse saturation current, spectral response and diffusion length. In the following sections, the various diagnostic approaches and the information that can be obtained will be discussed.

I-V CURVE ANALYSIS

The curves presented in figure 6 represent somewhat idealized cases. Only single failure modes are shown in each curve. In practice, several failure modes can, and usually do, occur together. From inspection of the solid curves alone, it can be seen that different failure mechanisms can have similar shapes in the power (4th) quadrant. Thus the ability to bias the cell in both the forward and reverse direction is essential. Figure 6b represents a junction that has a high excess diode current; this leads to poor fill factors and good currents. The open circuit voltage is not usually affected except in extreme cases. A low shunt resistance (figs. 6c & g) produces a poor fill factor and oftentimes reduced open circuit voltages. High series resistance (fig. 6d and f) reduces fill factor, but generally does not affect voltage. In extreme cases (fig. 6f), short circuit current is reduced. Biasing in the reverse direction will indicate the true light generated current. Also, the forward diode characteristic becomes more linear with high series resistance. A non-ohmic contact (fig. 6e) is most often seen as a curvature near open circuit voltage but may also occur near short circuit current in some devices.

These few idealized examples serve to indicate the scope and importance of the I-V curve as a diagnostic tool. The other diagnostic tools serve only to further confirm and determine the magnitude of the physical factors affecting device performance.

SERIES RESISTANCE MEASUREMENT

Cell series resistance is an important factor in improved cell designs. Measurement of its magnitude is necessary to continued device improvement, especially for devices exposed to concentrated sunlight. The following techniques are most commonly used.

Easiest to use is the far forward characteristic (5) in which the voltage drop between 300 and 400 mA (for a 1x2 cm cell) is used to obtain the series resistance. The value obtained generally represents a lower limit and is composed of bulk and contact resistance. The exact values of the forward current are not critical so long as the I-V curve is linear. In practice, the minimum forward current is about 3 to 6 times the cell short circuit current.

The next most common techniques for obtaining series resistance were described by Wolf and Rauschenbach (6). The two light level method requires two I-V curves obtained at different intensities. Cell series resistance can be computed from the short circuit current difference between the two curves combined with the voltage shift of a point on the I-V curve. It should be noted that series resistance values obtained with this technique generally depend on the point selected on the I-V curve. This can lead to erroneous results.

The next two techniques require the use of the V_{OC}-I_{SC} (open circuit voltage-short circuit current) characteristic of the cell. This characteristic is obtained by determining the V_{OC} and I_{SC} of I-V curves generated over a wide range of light intensities. Each V_{OC}-I_{SC} combination is plotted as a single point on an I-V or log I vs V characteristic. Use of these two points from the I-V curve eliminates the effect of series resistance, so long as the short circuit current equals the light generated current. In the case of high series resistances, reverse biasing must be used to obtain the light generated current. To obtain the series resistance, the V_{OC}-I_{SC} characteristic is subtracted from either the dark forward or the illuminated forward characteristics. (The illuminated forward characteristic is obtained by subtracting light generated current from the I-V curve.) An example of this technique for the dark characteristic is shown in figure 7. It can be seen that there is little difference between the two curves until the voltage reaches about 0.6V. The voltage difference between these curves at a fixed current is due to the device series resistance. Values of series resistance obtained by this technique are accurate. Small differences between series resistance in the dark and light are seen but are to be expected from theory.

REVERSE SATURATION CURRENT

For many analyses, the reverse saturation current (Io) and the slope of the forward diode characteristic are of importance. Techniques used to obtain these parameters are generally not detailed in technical reports. Some methods used are not accurate and have led to erroneous conclusions. Figure 8 shows a typical forward diode characteristic. Because this curve is composed of the sum of a variety of diode currents (e.g., diffusion, generation-recombination, shunt and surface), the component parts must be resolved in turn. Through this procedure, an accurate assessment of the magnitude and type of current present can be made. For example, the solid curves indicate the resolution of two of these components. No prior knowledge of the slope of the curve is needed for this procedure. Were the raw data to be used, significant errors in the slope of the diffusion component (A=1) and its intercept (Io) would occur. While somewhat more time consuming, subtraction of the component curves (beginning with the lowest current component, ususally the shunt resistance) appears to be the most reliable way of reaching firm conclusions.

SPECTRAL RESPONSE

Solar cell spectral response provides the most diagnostic information next to the I-V characteristic. In this approach, monochromatic lights illuminate the cell and the current produced is measured. Monochromators and narrow band pass monochromatic interference filters are the most common sources of light. Monochromators can range continuously but are limited in area coverage, uniformity and intensity. Interference filters do not suffer from these limitations, but their response gener.lly cannot be continuously varied over a wide range. Figure 9 shows a system using interference filters. This system as shown does not employ a white bias light to simultaneously illuminate the cell. Simple modifications to permit use of bias light are shown in figure 10. The bias light enters through a side port and is reflected onto the cell. Neither monochromatic nor bias lights are chopped in this system. In other systems, the monochromatic beam is chopped, while the bias light remains direct current. Either approach can be employed with the bias light system and comparable results are obtained. Bias light must be used in cases where cell performance depends on injection level or wavelength. Impurities or induced defects can lead to injection level effects while light ionized recombination or trapping cneters can lead to wavelength dependence. An example of a wavelength dependent spectral response behavior is the Cu_2S-CdS solar cell shown in figure 11. With no bias light, the response of this cell falls sharply above 0.7 μm. Slow current decays are also seen (7). However, the presence of bias light eliminates these effects and a reproducible spectral response is obtained.

The additional advantage of spectral measurements is that the quantum yield of the device can be obtained from the spectral response curve. Quantum yield is defined as electrons generated per photon incident. Such a curve for the Cu_2S-CsS cell is shown in figure 12. This information leads to a basic understanding of cell losses that can lead to future device improvements.

In all spectral response measurements, absolute accuracy is a substantial problem. Peak accuracy is no better than ± 5% at the present time. In practice errors of ± 20% are not unusual (8). Thus intercomparison of data from different sources is risky, and conclusions based on such comparison may not be warranted.

DIFFUSION LENGTH/LIFETIME MEASUREMENT

The measurement of diffusion length or lifetime of minority carriers in a solar cell is needed for modelling, process control and device improvement. A variety of techniques, such as shown in Table III, have been used in the past. This list is not all-inclusive but represents most of the common approaches.

When penetrating radiation is employed, the current collected for a fixed input is proportional to diffusion length. Calibration curves showing this proportionality are obtained both theoretically and experimentally (9, 10), Comparable results are obtained with electrons, x-rays and infrared light. Cells containing a junction or barrier layer are necessary. In general, this technique is the quickest to use.

The photoconductive decay method measures the response of a sample of material to a short pulse of light. After cessation of the light pulse, the light generated carriers decay with a time constant proportional to the lifetime. Sample geometry and carrier trapping are variables in this approach. Interpretation of the data can be time consuming.

Steady state photoconductivity and surface photovoltage measurement are techniques that can be used on bulk material or devices. They are generally more time consuming than the penetrating radiation approaches but also yield comparable results.

Electrical techniques for obtaining lifetime generally employ forward then reverse biasing of a device with an electrical pulse. The decay of the voltage or current (short circuited device) in the device after cessation of the pulse yields the lifetime. An example of an open circuit voltage decay curve is shown in figure 13. The sharp drop after cessation of the pulse (t = 0) yields device series resistance while the slope of the curve after t = 0 yields the lifetime. In general, sample size may be limited due to capacitance effects. Surface effects can also influence results. While these methods all yield comparable results, all require careful attention to obtain consistency.

CONCLUDING REMARKS

The art of solar cell measurement and diagnosis is more complex than is often recognized and requires a high degree of competence to achieve accurate, reproducible results. Considerable experience has already been built up. It is strongly recommended that those entering this field consult with experienced solar cell investigators to gain the benefit of their experience. In so doing, uniform measurements and accurate data will result which will hopefully lead to rapid progress in device development and improvement.

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TABLE I - LIGHT SOURCES USED FOR PERFORMANCE MEASUREMENT

- SUNLIGHT
- TUNGSTEN LAMPS
  - ELH LAMP (~ AM2)
  - 3400^{0} K LAMP PLUS WATER FILTER
- XENON ARC LAMPS
- PULSED XENON LAMPS

TABLE II - TYPES OF EQUIPMENT FOR I-V CURVE MEASUREMENTS

- FIXED LOAD RESISTOR BANK
- VARIABLE POWER SUPPLY (BATTERY ETC.)
- ELECTRONIC LOAD
- CALCULATOR-CONTROLLED ELECTRONIC LOAD AND DATA ACQUISITION AND REDUCTION SYSTEM

TABLE III - TECHNIQUES FOR DIFFUSION LENGTH/LIFETIME MEASUREMENT

OPTICAL

- PENETRATING RADIATION
  - X-RAYS
  - 1 MeV ELECTRONS
  - INFRARED LIGHT ($1.1 > \lambda > 0.9\ \mu m$)
- PHOTOCONDUCTIVE DECAY
- STEADY STATE PHOTOCONDUCTIVITY
- SURFACE PHOTOVOLTAGE

ELECTRICAL

- OPEN CIRCUIT VOLTAGE DECAY
- COLLECTION OF STORED CHARGE (CURRENT DECAY)

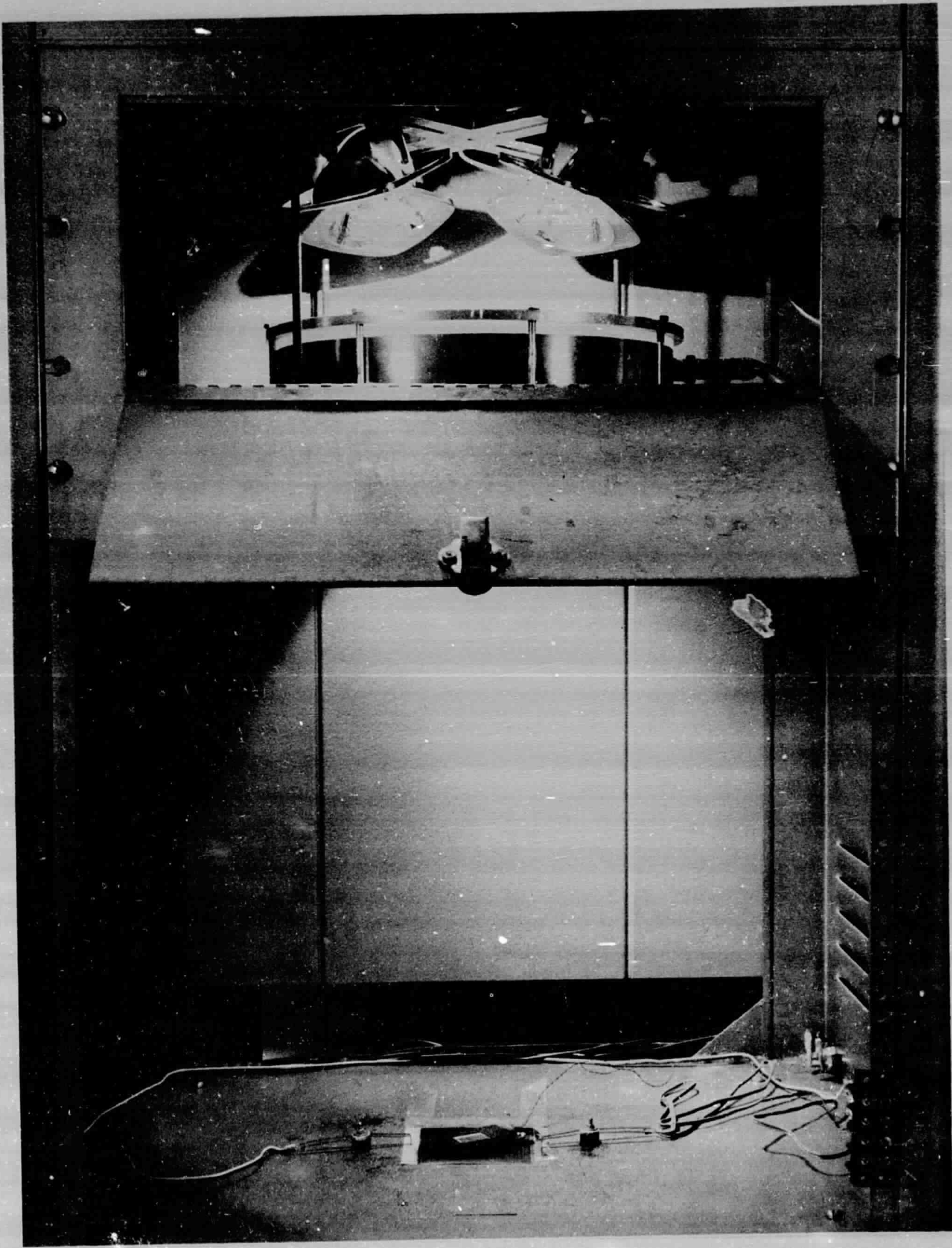

Figure 1. - Tungsten Light Solar Simulator

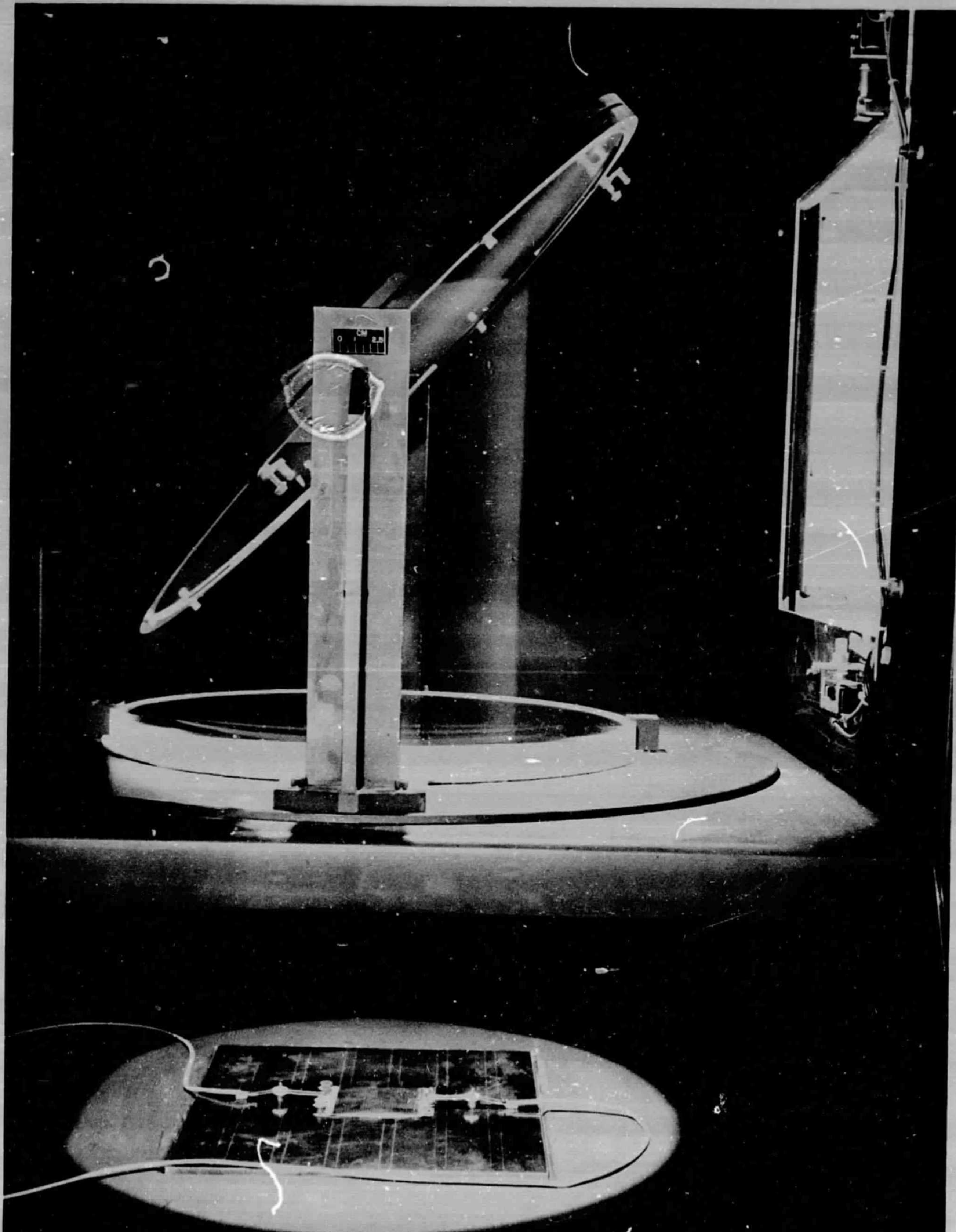

Figure 2. - Test Plane of Steady State Xenon Arc Simulator

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SPECTRAL DISTRIBUTION OF SOLAR SIMULATORS

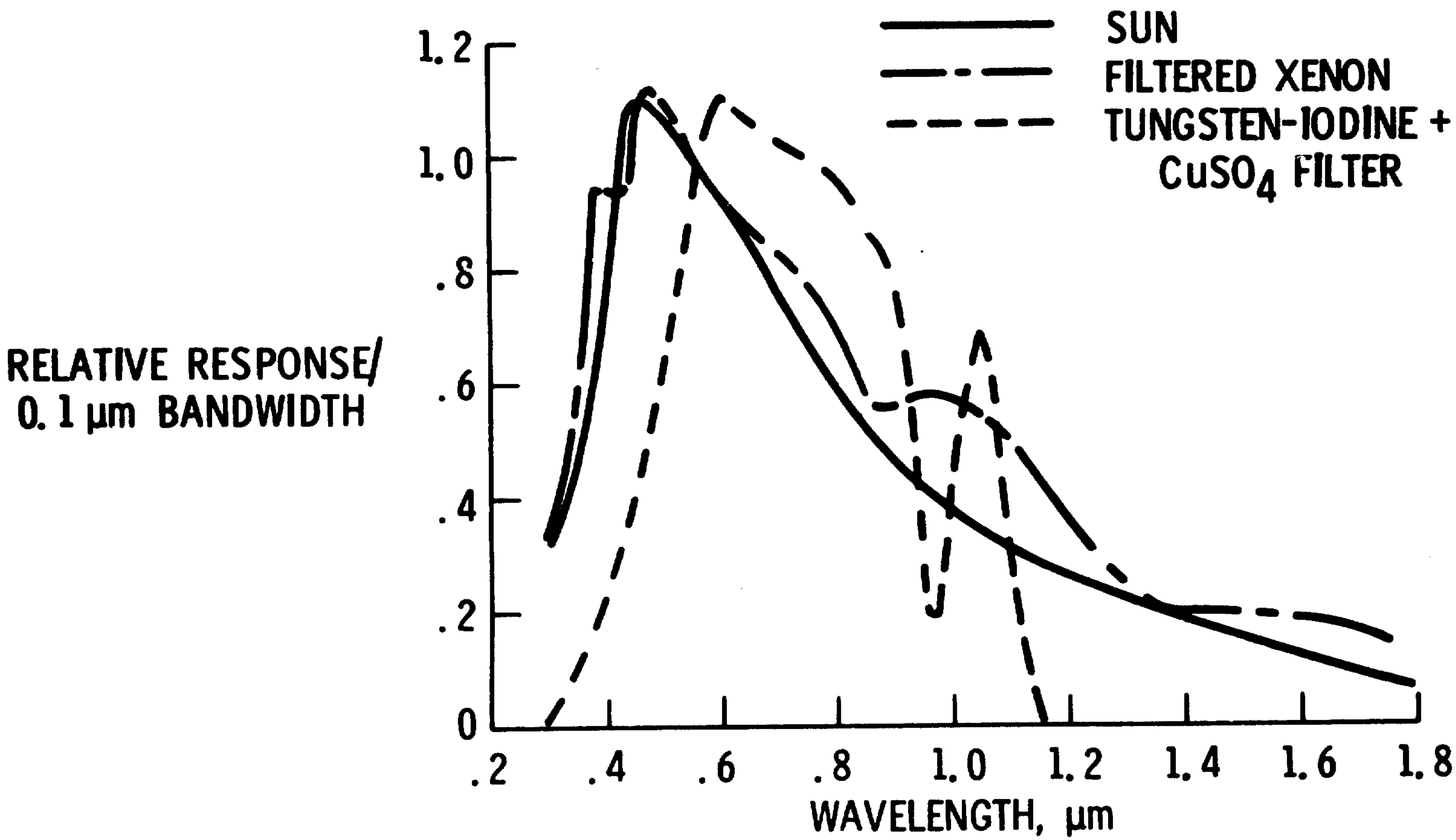
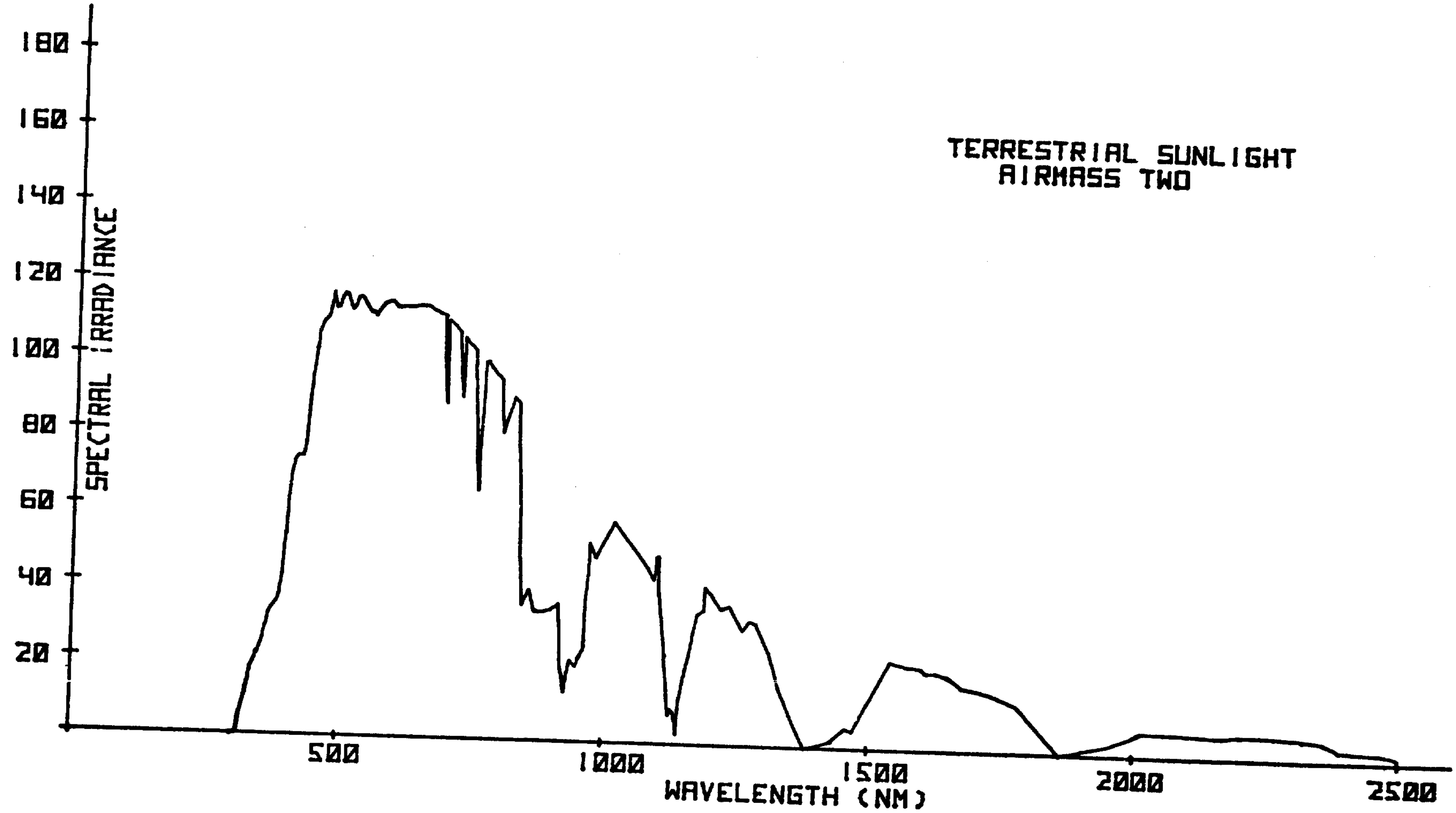


Figure 3.

Figure 4. - Spectral distribution of terrestrial sunlight



CURRENT-VOLTAGE CURVES OF A Cu_2S-CdS CELL ILLUMINATED WITH RED AND WHITE LIGHT

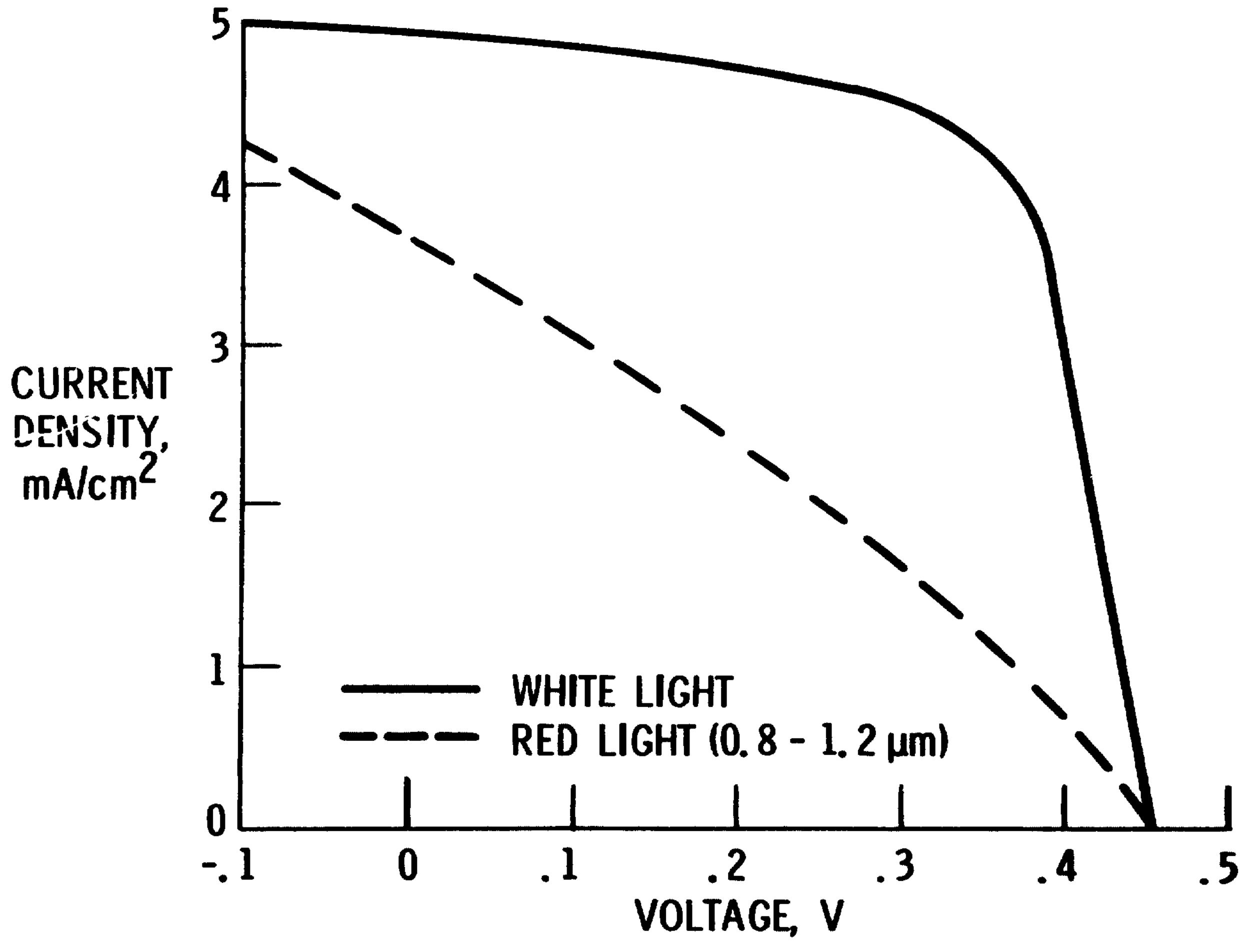
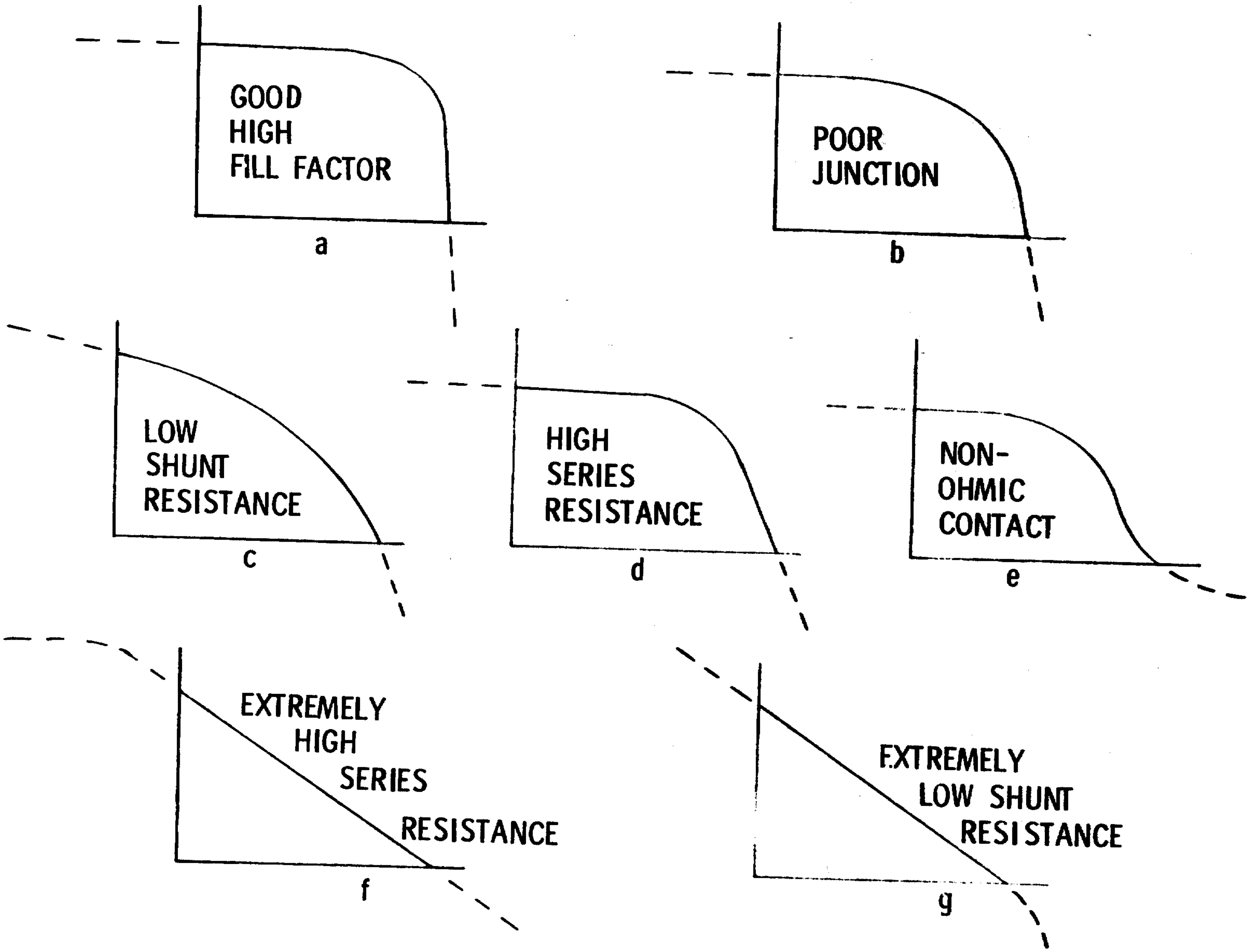


Figure 5.

Figure 6. - Solar cell current-voltage characteristics
(Current axis, vertical, voltage axis horizontal)



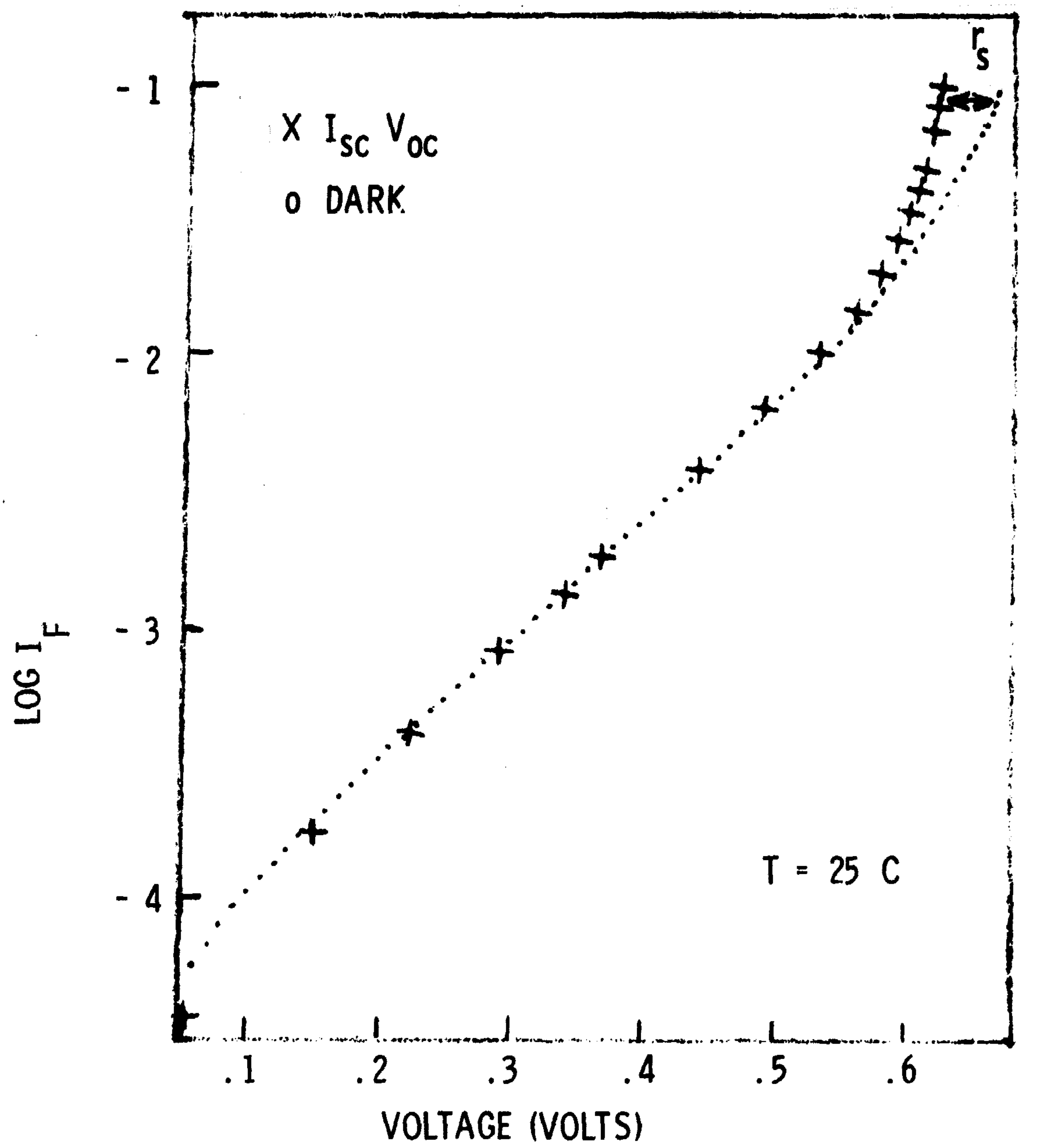


Figure 7. - Solar cell forward I-V characteristics measured by dark and illuminated methods

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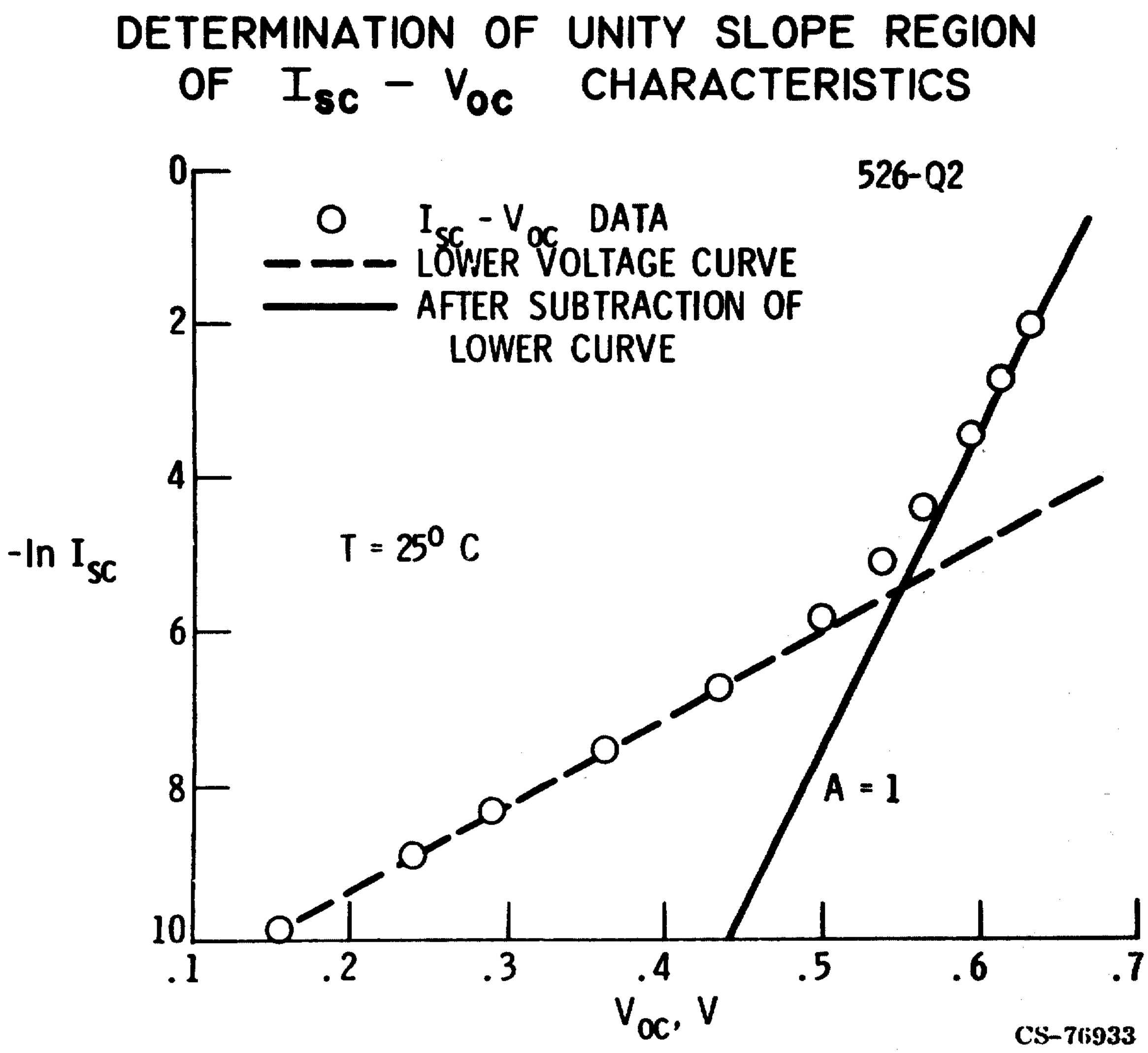

Figure 8.

APPARATUS FOR MEASURING SPECTRAL RESPONSE

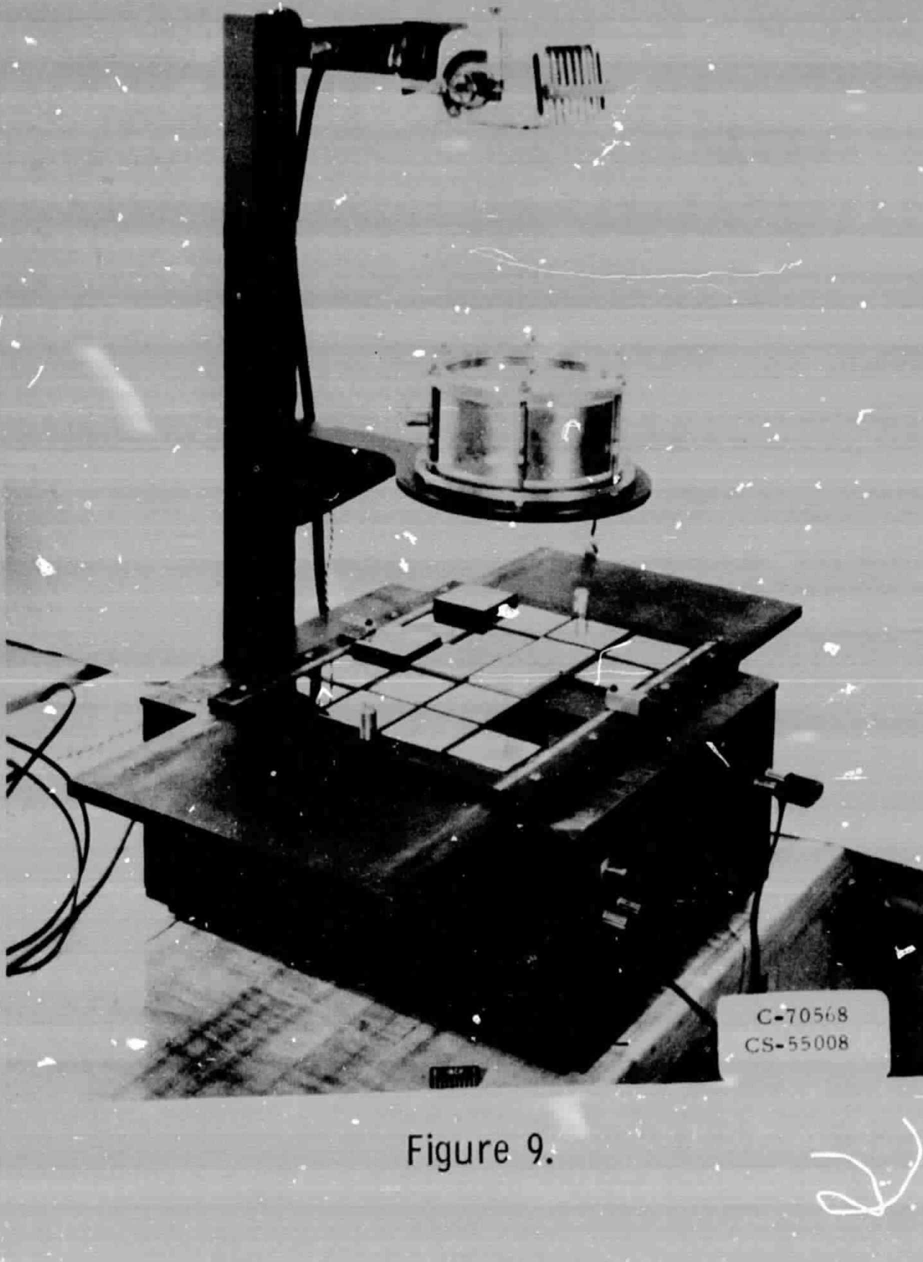

Figure 9.

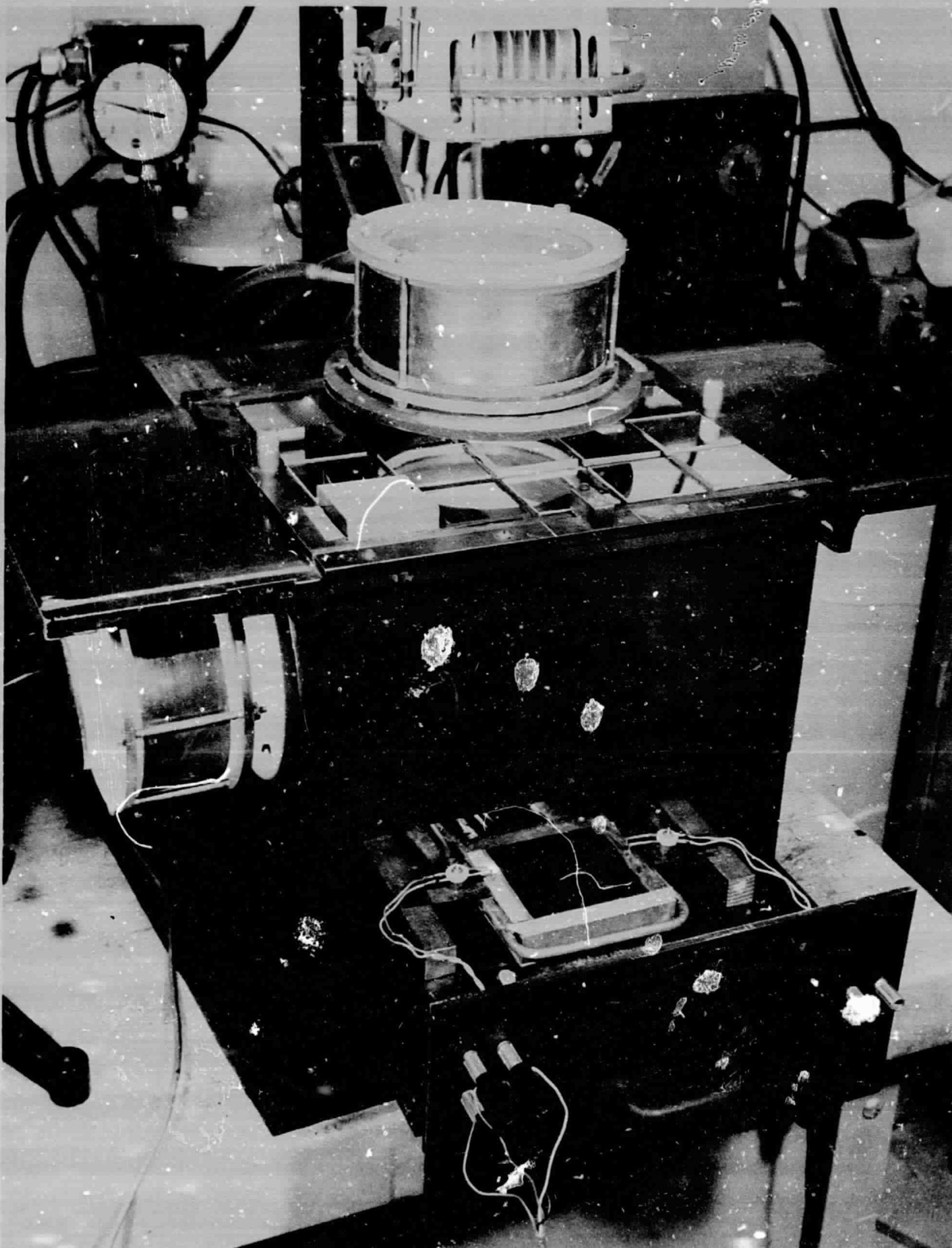

Figure 10. - Spectral response measurement with white light bias

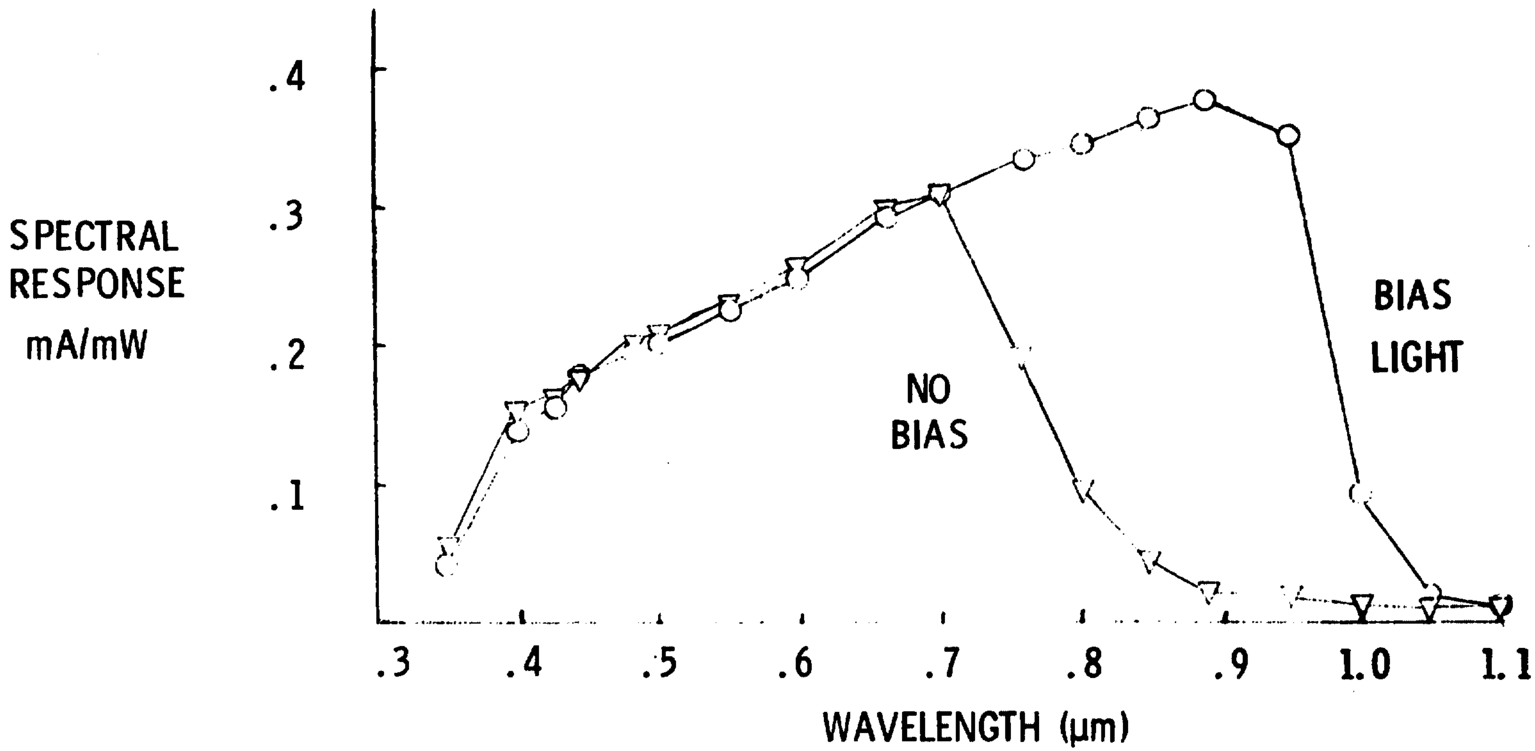

Figure 11. - Spectral response of a CdS solar cell

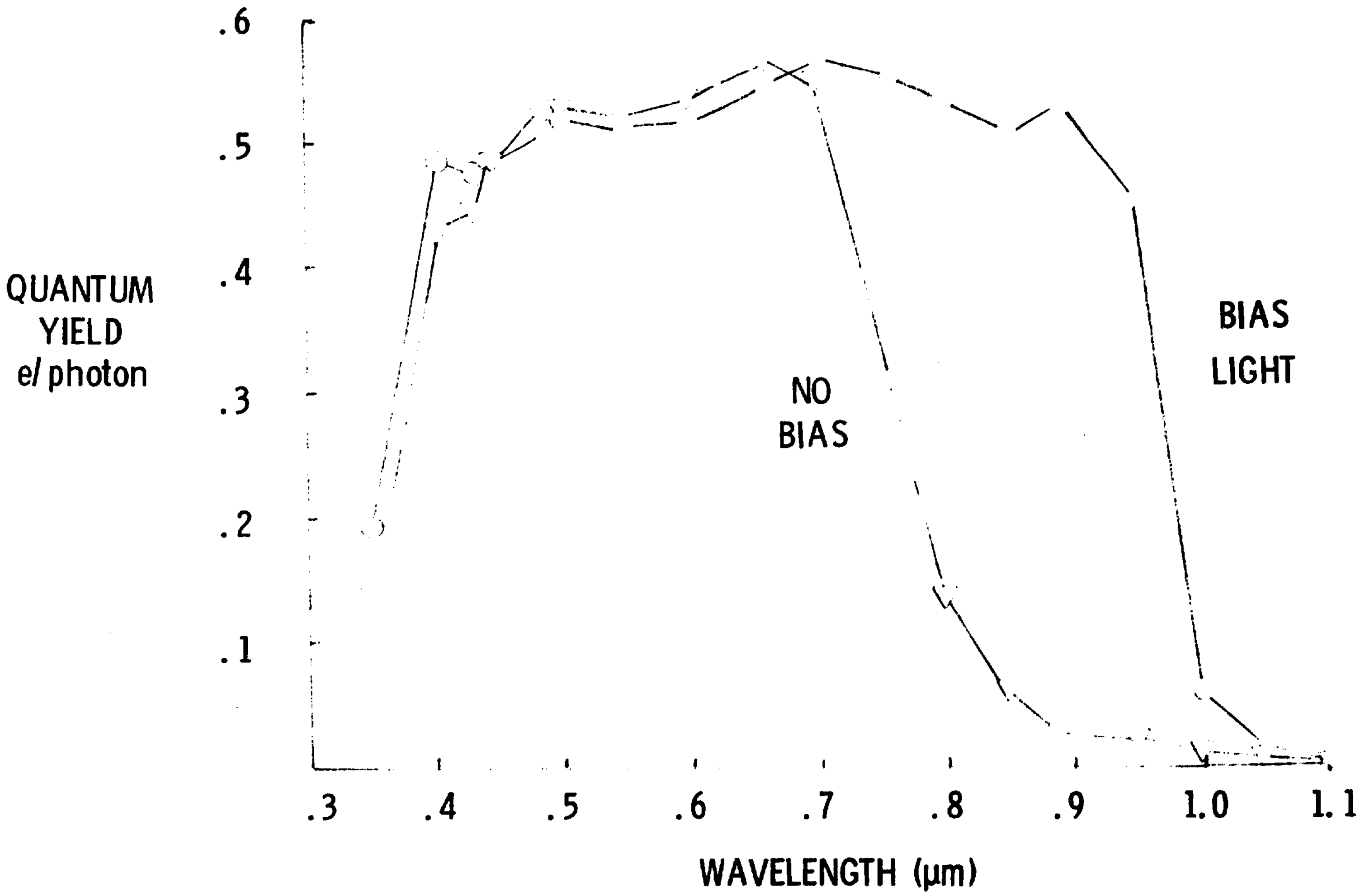

Figure 12. - Quantum yield of a CdS solar cell

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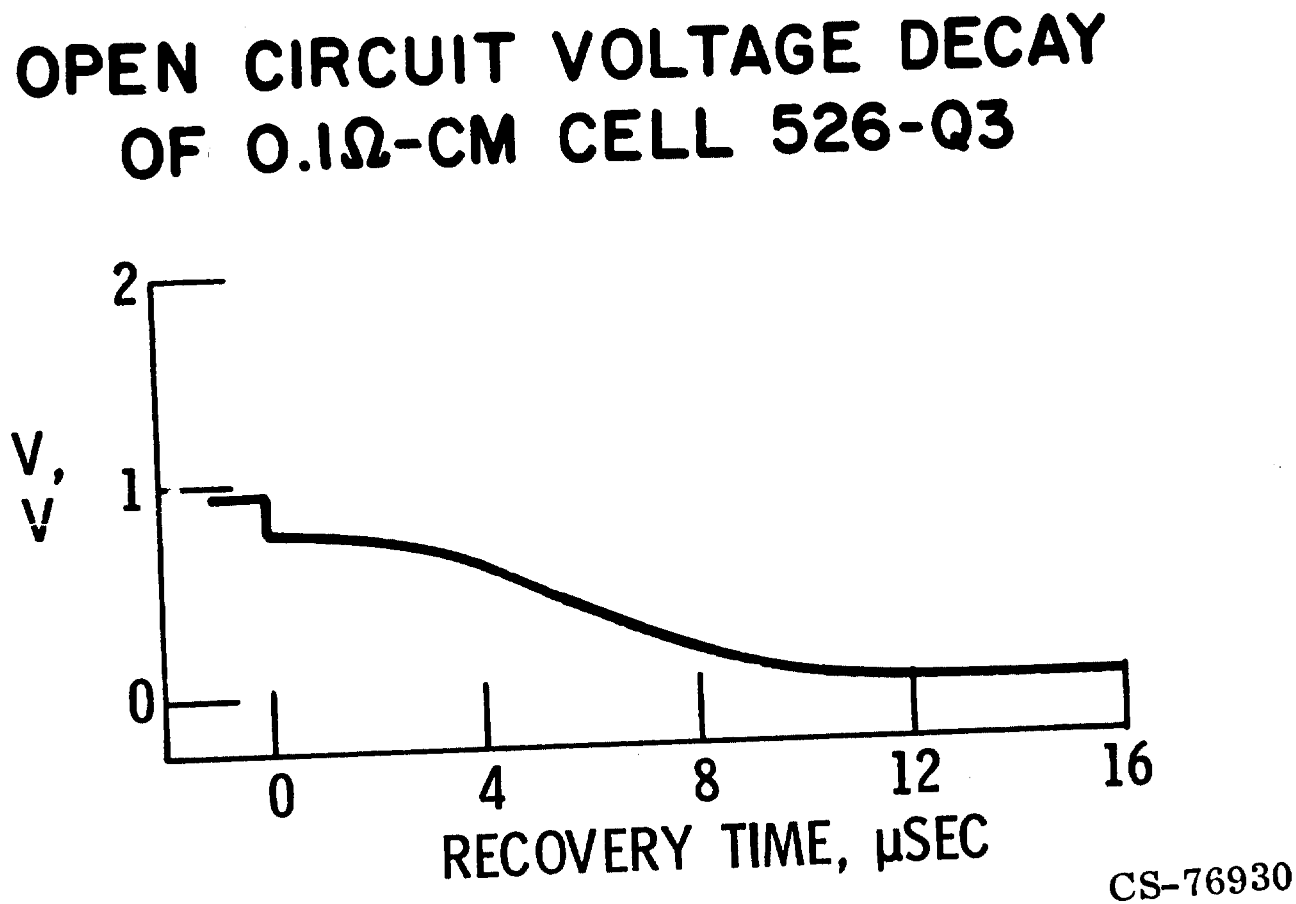

Figure 13.